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TECHNICAL REPORT ARBRL-TR-02075

# APPLICATIONS OF THE RADIOISOTOPE WEAR MEASUREMENT TECHNIQUE

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US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

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Erosive wear has been measured from gun steel surfaces by detecting the loss of the radioisotope $^{56}$Co which has been introduced into the surface layers. The $^{56}$Co activity is produced by means of the $^{56}$Fe(p,n) $^{56}$Co reaction when the steel is bombarded by a beam of protons. A detailed calibration curve, relating the amount of $^{56}$Co activity to the amount of surface material worn off, has been measured and is applicable to all steel surfaces. This method has a precision

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of ± 0.1 μm, can be performed in a short time, in-situ, and without surface cleaning. Three experiments in which this method has been used are discussed. In the first, a land on a 20 mm barrel was activated and the wear measured under several different firing conditions. In the second, wear was measured from an activated plug inserted into a land of the 20 mm barrel. In the third, steel erosion nozzles were exposed to several different propellants and wear losses as well as mass losses were measured. The correlation between the two methods is very good. Possible applications of this method to a variety of wear measurement experiments are discussed.

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## 1. INTRODUCTION

Evaluation of erosive wear in gun tube systems has been a difficult problem for the Army for a long time. It is a problem because the amount of wear occurring with a single shot, or a small number of shots, is usually too small to be measureable by star-gauging (micrometer) methods. Consequently, large amounts of munitions must be expended at sometimes great costs in money and time in order to determine the erosivity of any given gun barrel-propellant-additive-rotating band configuration. In addition, the accuracy of micrometer measurements can well be affected by the presence on the bore surface of foreign matter such as coppering from the rotating bands or propellant residues due to incomplete cleaning. This report describes the use of a radioisotope technique in:

(1) a very precise measurement of bore surface wear in a 20 mm pressure barrel,

(2) the measurement of wear from the 20 mm barrel by an activated plug, and

(3) the evaluation of the erosivity of two different propellants utilizing erosion nozzles and a 37 mm blow-out chamber.

In the radioisotope technique specific nuclear reactions produced by accelerator beams are used to transform stable materials into radioactive isotopes. The characteristic radiations emitted by these radioisotopes provide a means to monitor changes in the characteristics of the activated area of the surface. Activation of a small region of a surface to a prescribed depth allows a measurement of wear from that region by monitoring the decrease in the intensity of radiation due to the removal of surface materials.

Gun steel is particularly suited to the radioisotope technique since it consists primarily of $^{56}Fe$. When $^{56}Fe$ is bombarded with a beam of protons, a nuclear reaction can take place in which a free neutron and the radioactive isotope $^{56}Co$ are produced. $^{56}Co$ has a half-life of 77.3 days and decays to $^{56}Fe$ producing a characteristic gamma ray spectrum. The proton beam loses energy as it penetrates into the steel, and once its energy has fallen below the reaction threshold energy of 5.45 MeV, no more $^{56}Co$ is produced. Thus, the $^{56}Co$ is distributed in a well defined surface layer, the thickness of which is determined by the initial proton beam energy. The amount of wear due to exposure to erosive environments can then be determined by a measurement of the loss of intensity of the emitted gamma-rays from the surface. The primary advantages of this technique are: i) all

measurements can be performed in-situ; ii) the measurement is independent of surface contaminants and thus the surface needs no cleaning prior to measurement; iii) the precision of the measurement is approximately ± 0.1 μm (0.000004") - 250 times better than the widely used star-gauging method. For a detailed description of the method and its calibration technique see References 1 and 2.

## 2. EXPERIMENTAL PROCEDURE

### 2.1. 20 mm Barrel.

An unplated 20 mm pressure barrel was prepared for activation by machining three holes into its wall; one at the origin of rifling, one in the middle, and one at the muzzle end. The holes were positioned so that a proton beam could enter through each hole and strike a land on the opposite side of the barrel, activating a spot of about 1.5 mm diameter to a depth of approximately 25 μm. (See Figure 1, top.) The activation was performed at the Tandem Van de Graaff Laboratory of the University of Pennsylvania. The barrel was then mounted in an indoor firing range at BRL. The three holes were pressure sealed by ball bearings held in place by bolt and clamp arrangements as shown in Figure 1, bottom.

The gamma-ray activity was measured with a 7.5 cm X 7.5 cm NaI scintillation detector whose output pulses were recorded by a multichannel analyzer. Since the attenuation of the 1 MeV gamma-rays from $^{56}$Co through the roughly 20 mm steel wall of the barrel does not affect the precision of the wear measurement, the detector was mounted outside the barrel. The reproducibility of the detector position from measurement to measurement, a critical aspect of this technique, was accomplished by a self positioning detector holder. From 5 to 10 cm of lead shielding was placed around the NaI scintillator to reduce both room background and cross-talk between the three active spots. The activity at each of the three positions was measured before any shots were fired to establish a baseline for subsequent measurements. The geometry of the barrel-detector system is also shown in Figure 1, bottom. Two hundred and thirty-one M55A2 rounds of ammunition were fired. Twenty of the rounds had nylon rotating bands, ten rounds were coated with $TiO_2$ wax and the rest were standard rounds.

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1. Stephen E. Caldwell and Andrus Niiler, "The Measurement of Wear From Steel Using the Radioisotope $^{56}$Co", BRL Report No. 1923, September 1976. (AD #A030262)
2. Andrus Niiler and Stephen E. Caldwell, "The $^{56}$Fe(p,n) $^{56}$Co Reaction in Steel Wear Measurement", Nucl. Instr. and Meth. 138, 179 (1976).

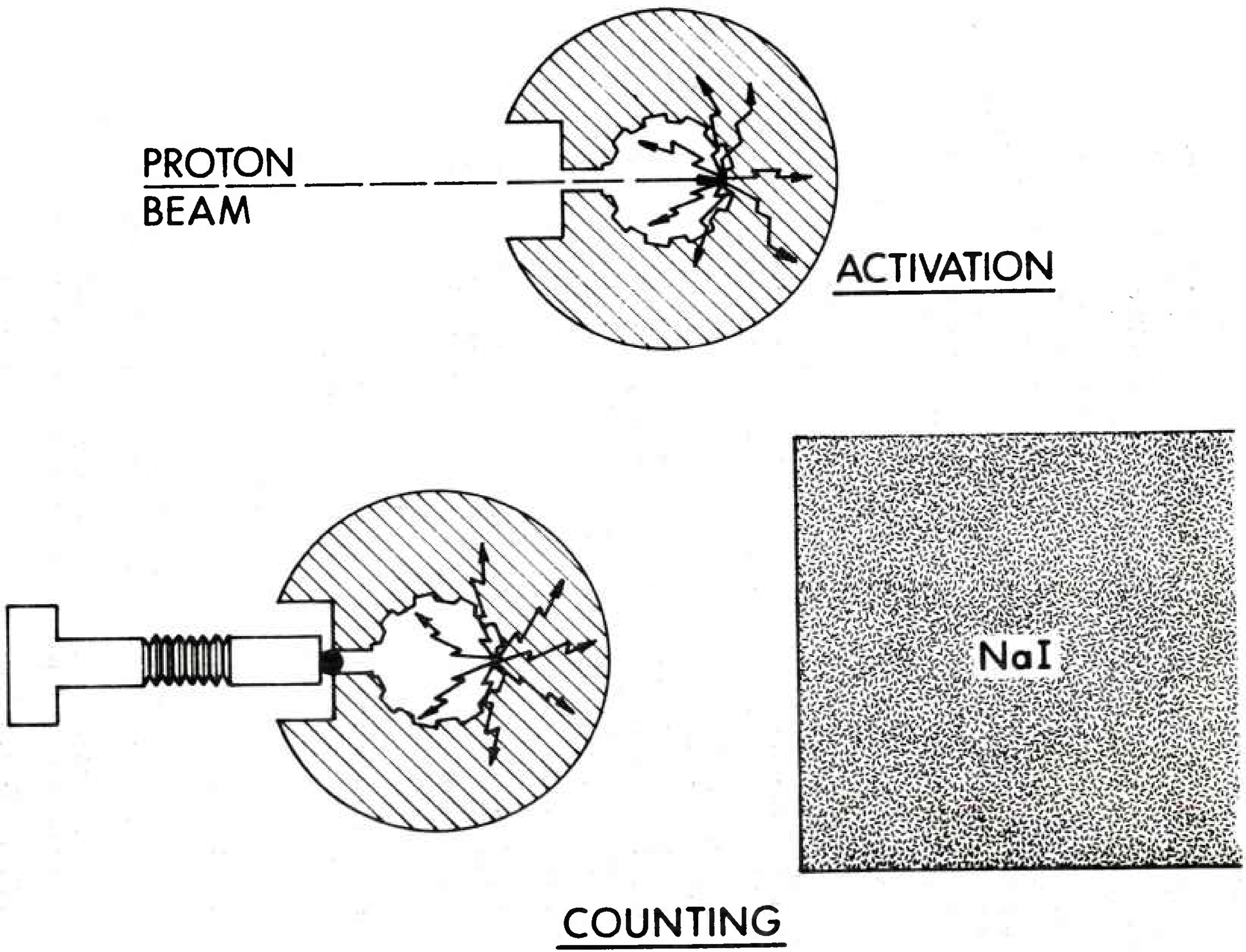



Figure 1. (Top) Schematic of the experimental arrangement for activation of a land in a 20 mm barrel. (Bottom) Geometry of barrel-detection system with ball-bearing pressure seal.

## 2.2. Radioactive Plugs.

A plug of heat-treated 4340 steel was machined to fit in a land in a 20 mm barrel at the same distance from the origin of rifling as the activated spot described in the previous section. Flushness of the plug face with the land surface was established by observation of the back-lighted plug-land profile with a telescope arrangement. The plug was then removed from the barrel and activated at the University of Pennsylvania. Subsequently, eighty rounds of M55A2 ammunition were fired through the 20 mm barrel with the plug being held in place by a bolt-clamp arrangement, and with the pressure seal being made by an "O" ring. The plug was removed from the barrel and the loss of gamma-activity determined after rounds of 1, 7, 11 and ten-round intervals thereafter.

## 2.3. 37 mm Nozzles.

A 37 mm vented chamber, shown in Figure 2, was used to expose nozzles of 4340 gun steel to propellants. As the propellant charge burns, the pressure increases and ruptures the mild steel disc. The hot gases stream through the nozzle, eroding the nozzle surface. Two propellants, M5 and a new high force (HFP) nitramine based propellant,[3] were tested to determine their relative erosivities. A separate nozzle was used for each propellant. The charge of the particular propellant was chosen so that the pressure-time trace was the same and so that the entire charge was burned. Both of the nozzles, which are of long-standing BRL design, were fired twelve times. A full report of the experiment to determine the HFP erosivity is being published separately.[4]

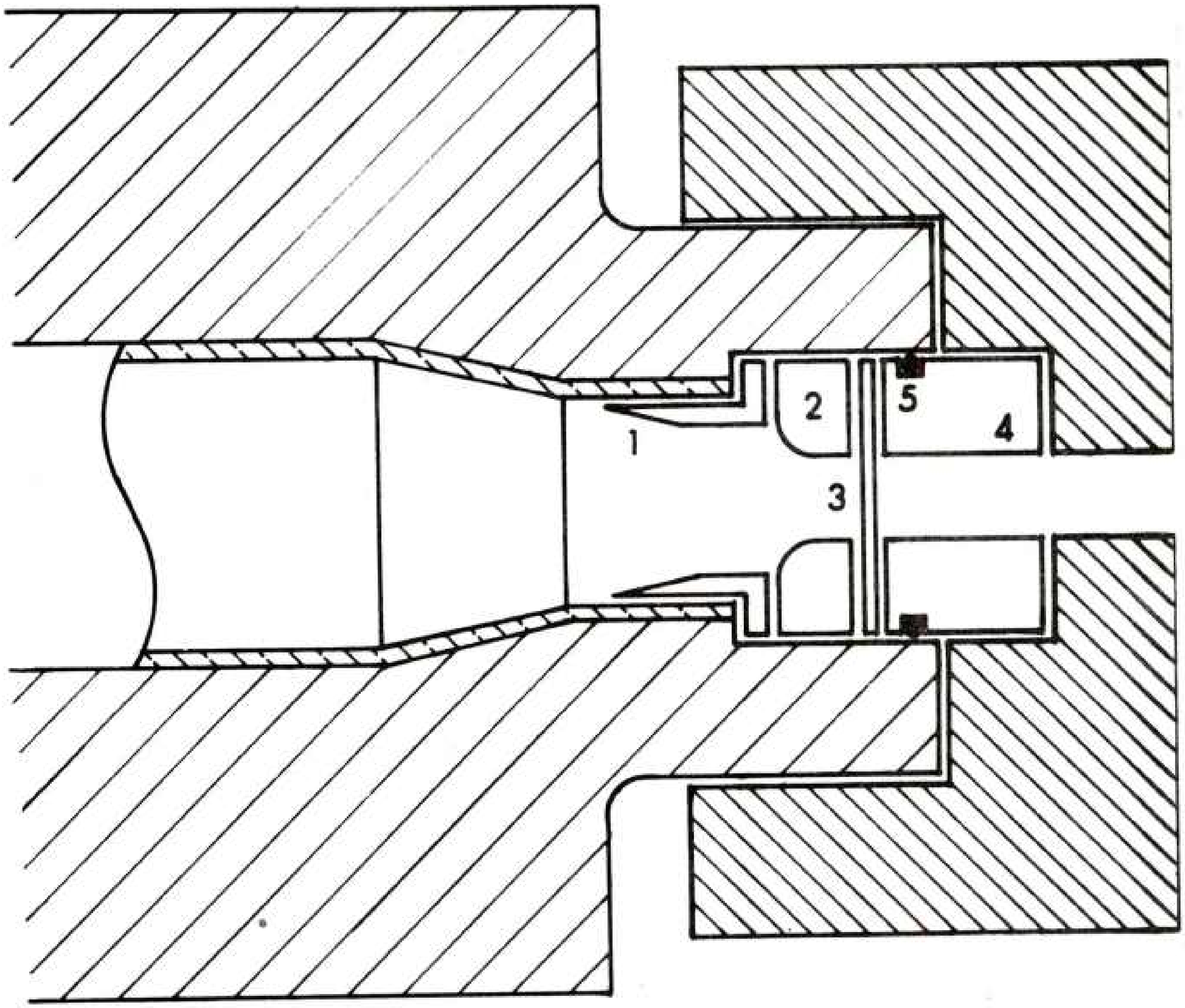
To evaluate the erosivity of the propellants, two independent measures were used. First, the nozzles were cleaned with detergent and weighed to determine the mass lost per round. This yielded an average mass loss over the entire exposed surface of the nozzle. Second, a 3 $mm^2$ area in the fast flow region of the nozzles had been activated with a 6.125 MeV proton beam. The decrease in gamma-ray activity was measured after each shot, thus giving a measure of the wear in a localized region.

# 3. RESULTS

## 3.1. 20 mm Barrel.

The first activity measurement was made after a single M55A2 round had been fired. No measureable loss in activity was detected at any of the three activated spots. Next, a 10-round burst was fired at 2 rounds per minute and a loss in activity was recorded at the origin of rifling. No measureable loss was recorded at the other two activated spots. The

3. Obtained from ARRADCOM, LCWSL, Dover, NJ., Lot PPL-A-6380.
4. R.W. Geene, J.R. Ward, T.L. Brosseau, A. Niiler, R. Birkmire and J.J. Rocchio, "Erosivity of a Nitramine Propellant", to be published as a BRL Report.




1. RETAINING RING
2. NOZZLE
3. BLOWOUT DISC
4. SPACER
5. O-RING SEAL

Figure 2. 37 mm Vented Chamber

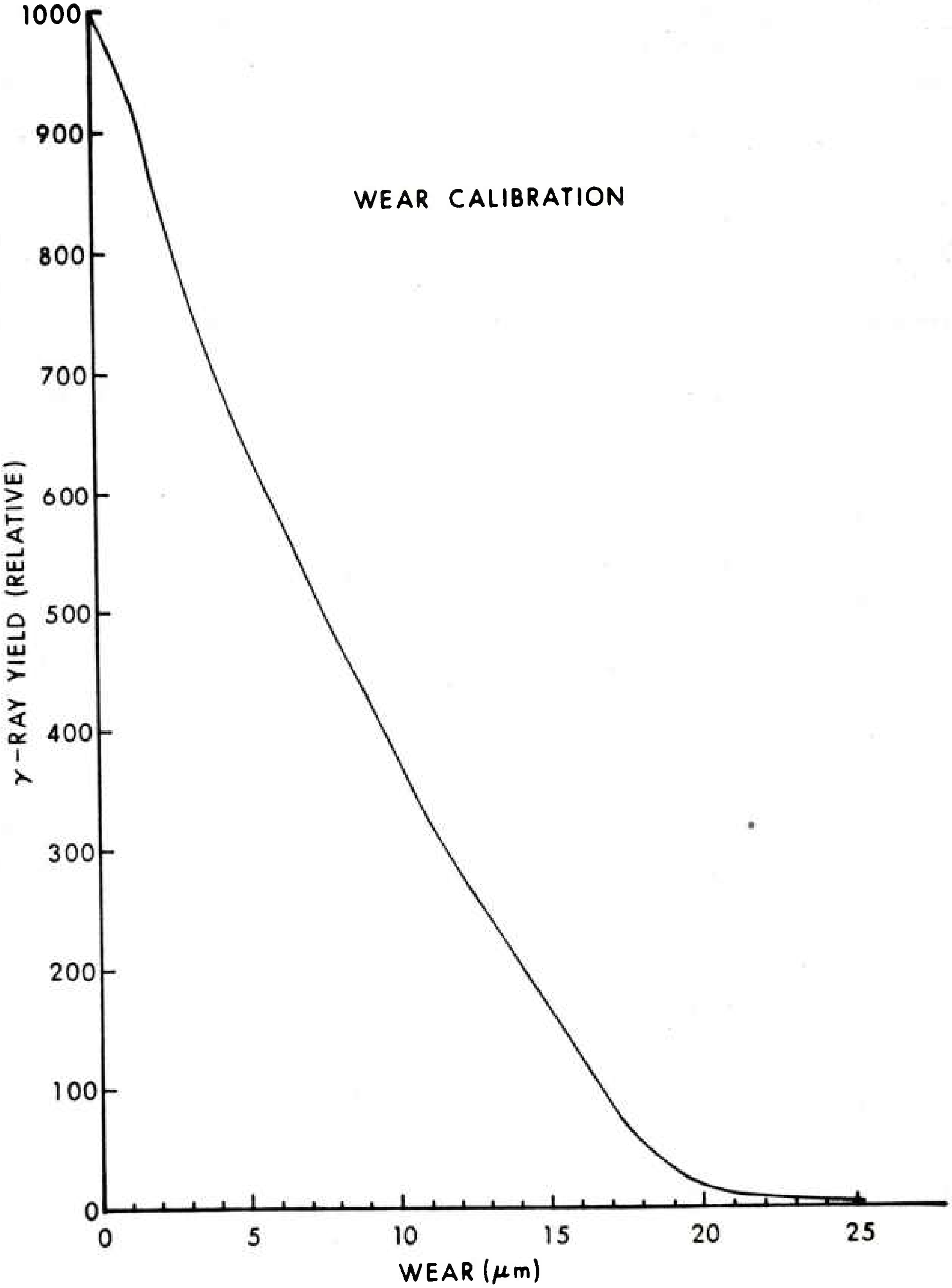



Figure 3. Calibration curve displaying the gamma-ray yield as a function of the activated layer depth. (From Reference 1).

relative loss in activity was converted to loss of surface steel through the calibration curve shown in Figure 3. The details of how this curve was obtained can be found in references 1 and 2. The subsequent firing program consisted mainly of 10-round bursts fired at 2 rounds per minute and one 50-round burst at the same rate. Activity measurements were made after each of these ten or fifty round bursts and the results are shown in Figure 4 for the spot at the origin of rifling. Little or no wear was recorded at either of the other activated spots.

A discussion of the results displayed in Figure 4 is in order. Whenever two points are plotted at the same round number, it indicates two independent activity measurements, usually separated by at least 16 hours. The differences between any pair of points is indicative of the instrumental uncertainties in the measurements and amount to 0.1 μm or less. The following features of the results should be noted:

a). From round 31 through 171, the data points lie on a straight line indicating a constant wear rate of 0.023 μm/round ($9 \times 10^{-7}$ in/round).

b). Rounds 132 through 151 had nylon rotating bands but showed no difference in wear from the standard copper bands used for all other rounds in the experiment. Thus in the slow fire mode, it appears that nylon rotating bands <u>do not</u> reduce erosion wear as reported for the rapid, automatic fire mode[5]. The implications of these data to the Army's programs to reduce erosion in large caliber guns by use of non-metallic bands are very significant. At the very least, more tests are needed both in slow and fast fire modes with large and small caliber guns before large scale development is started.

c). Rounds 172 through 181 were standard M55A2 rounds but the projectile tips were coated with $TiO_2$ wax. It appears that the $TiO_2$ wax coating abraded the surface causing greater wear. The next ten shots (182 to 191) were standard rounds and also showed a higher wear rate. It is hypothesized that the abrasive $TiO_2$ wax "cleaned" the bore surface and that the subsequent rounds were eroding a "clean" surface rather than one which contained an altered layer of oxides, nitrides or whatever. Since the first thirty rounds also show higher wear rates, it might be speculated that the original bore surface had been clean, or at least was significantly different than the surface layer left behind by the firing of the M55A2 rounds. This hypothesis also implies that the condition of the surface layers is a very important factor in determining erosion rates. More definitive experiments are necessary to test this hypothesis.

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5. M. Shamblen and J. O'Brasky, "Naval Gun Barrel Wear and Erosion Studies", presented at the 1976 JANNAF Propulsion Meeting, Atlanta, Georgia, December 1976.

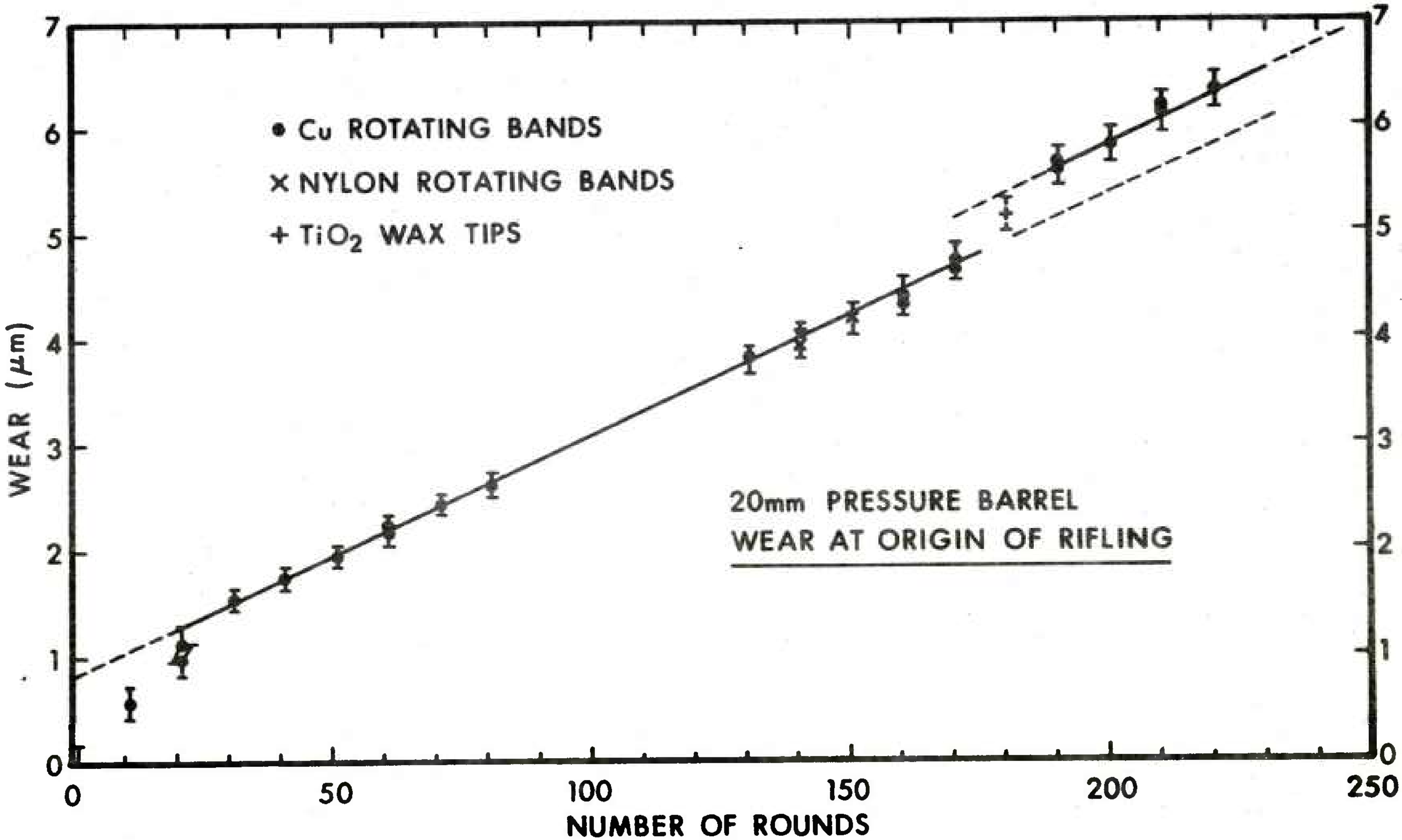


Figure 4. Surface material removed at the origin of rifling as a function of the number of rounds fired. The error bars are absolute errors; relative errors are smaller.

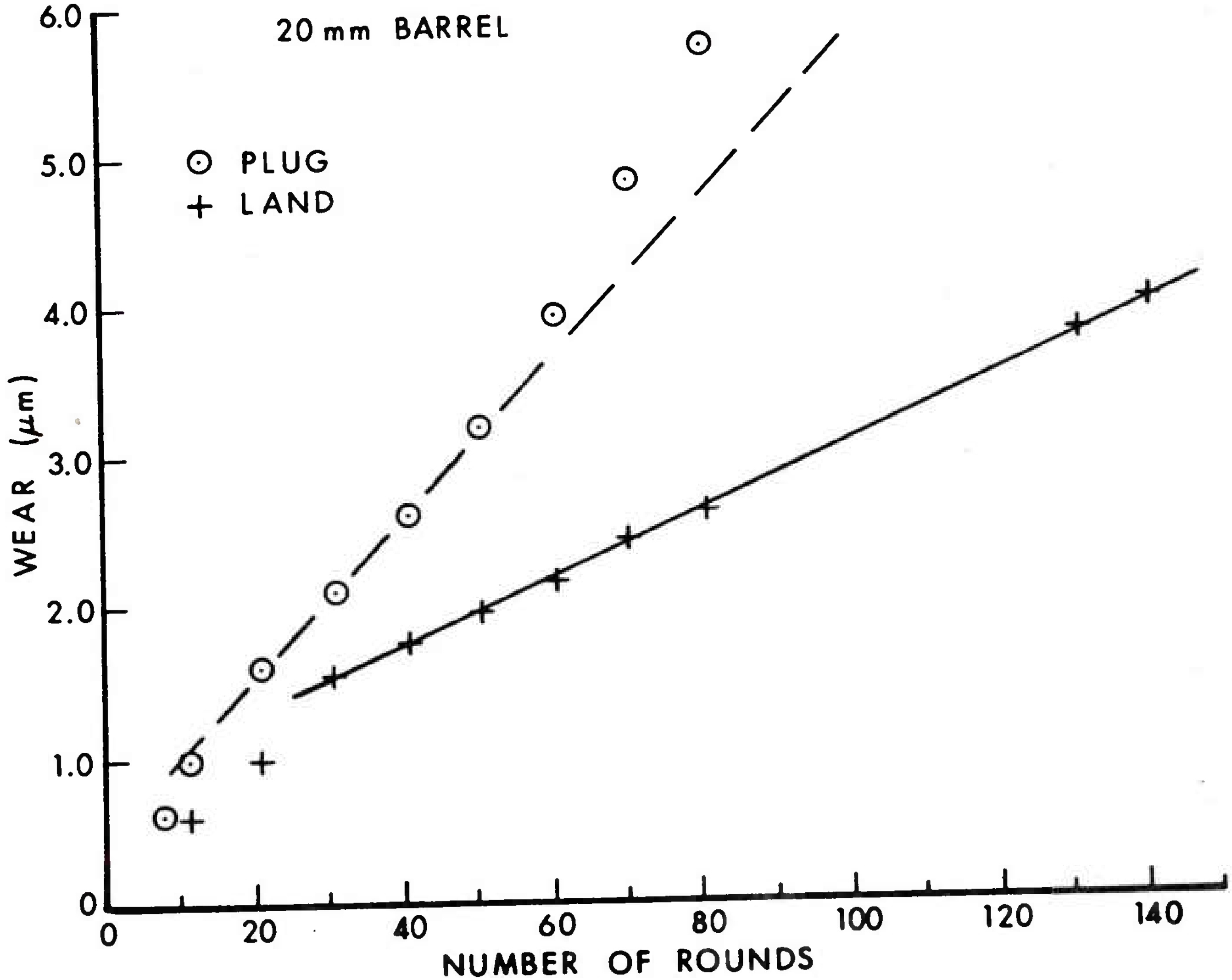


Figure 5. Comparison of wear from a 20 mm barrel land at the origin of rifling and a plug inserted in an adjacent land.

### 3.2. Radioactive Plugs.

The results of firing the 20 mm barrel with the radioactive plug are shown in Figure 5 along with the activated-land results. As can be seen, the plug wears at a significantly higher rate than the land and also deviates from a linear wear rate after 60 rounds. A number of reasons may have contributed to this difference between the wear rates from the plug and the land: a) The width of the land in the 20 mm barrel is quite small (1.9 mm) and it is difficult to machine a plug that fits accurately into such a small land. b) Only a small portion of the surface of the plug was activated due to a misalignment of the plug and accelerator beam. This fact might exaggerate the wear measurement error if the wear should be non-uniform over the surface of the plug. c) The lands in the 20 mm barrel were worn before the plug was inserted so the plug cannot be made to fit flush with the land surface. In addition, bore scope pictures taken after the 80 rounds were fired showed some land deformation in the area of the plug as well as rounding of the hole edges. Consequently, it is felt that the results were not conclusive in establishing the usefulness of plugs in barrel wear measurements. The fact that for the first 60 rounds the wear was approximately linear is encouraging since a good relative measurement in evaluating propellants might be possible in that many rounds.

### 3.3 37 mm Nozzles.

The results of the wear and mass loss measurements for the M5 and HFP propellants are shown in Figures 6 and 7, respectively. In general, the trend in the data indicates quite good agreement between the two different measurements, the M5 being a more erosive propellant than HFP. The HFP results show a constant wear rate for the entire twelve rounds while the M5 data deviate from this constant rate after eight rounds. The solid lines on both figures were obtained by least squares fits to the data, with the last four M5 data points being omitted in the fitting. The correlation between the mass loss and wear is shown in Figure 8 for both the M5 and HFP propellant data. The high degree of correlation between the two measurements (correlation coefficient = 0.995) is a clear indication of the reliability of both techniques for measuring wear. However, there are subtle differences in what can be determined by these two methods. The radioisotope measurement yields a wear loss at a small ($\sim 3mm^2$) spot while the mass loss gives an average wear over the exposed surface. In this case, the average wear derived from the mass loss measurements is about twice as high as the wear measured at the activated spot. This implies that the exposed surface area of the nozzle does not wear uniformly even though it does wear at a constant rate, shot to shot.

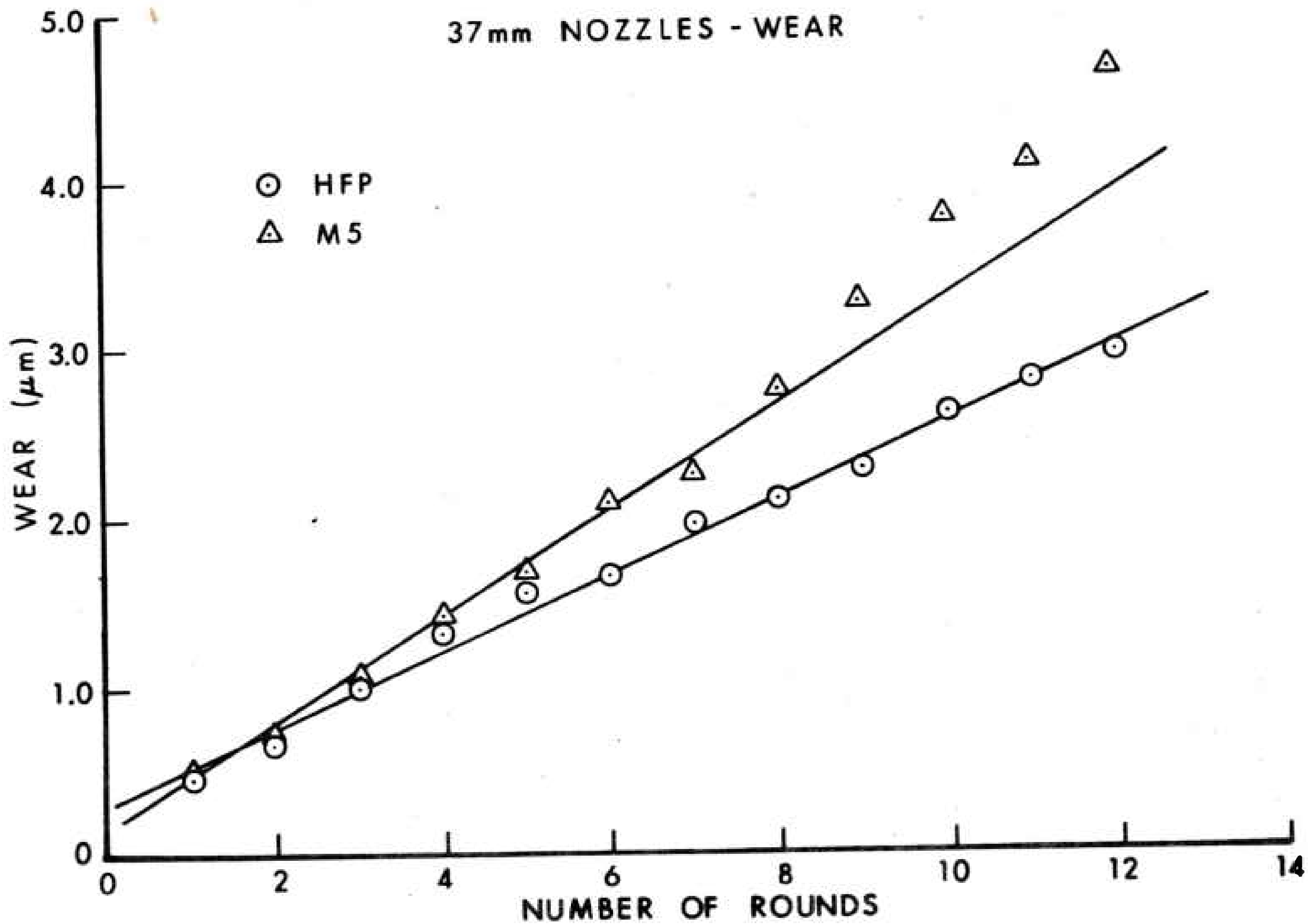


Figure 6. Nozzle wear as a function of rounds fired in the 37 mm vented chamber with M5 and HFP propellants.

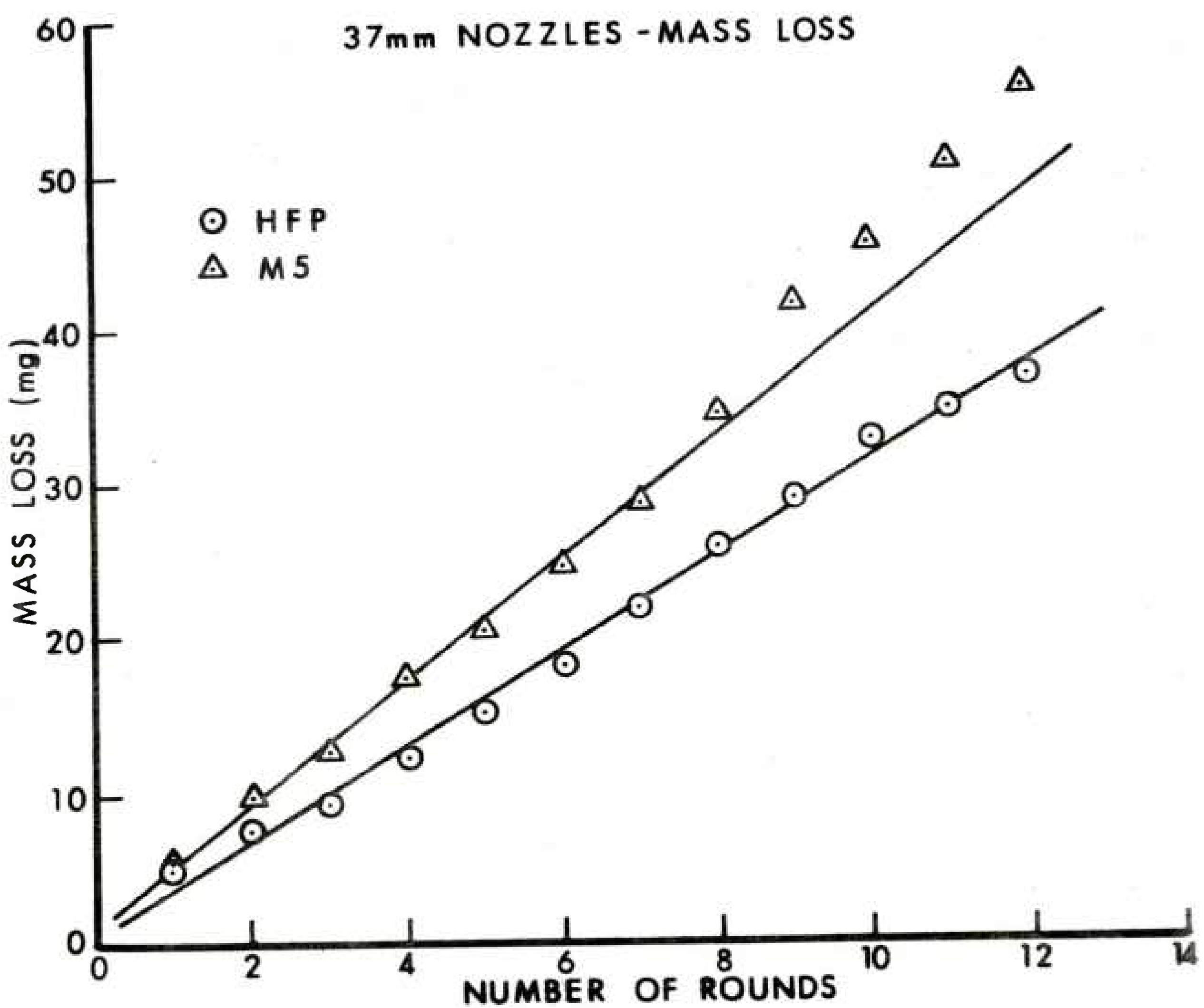


Figure 7. Nozzle mass loss as a function of rounds fired in a 37 mm vented chamber with M5 and HFP propellants.

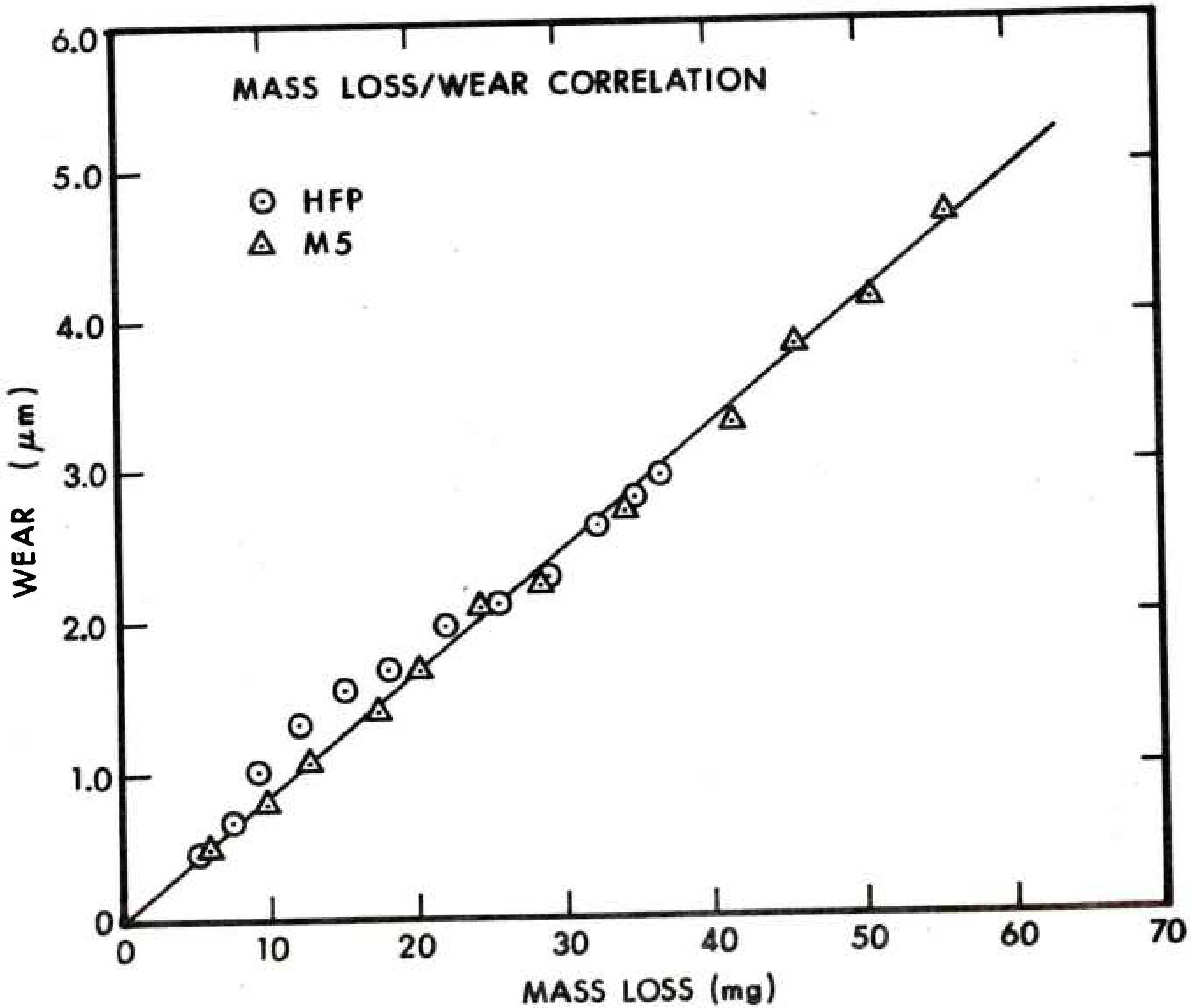


Figure 8. Correlation between wear and mass loss measurements from nozzles fired in a 37 mm vented chamber with M5 and HFP propellants.

## 4. CONCLUSIONS

The use of a radioisotope technique in the evaluation of erosive wear has been demonstrated with a 20 mm barrel and 37 mm nozzles. In the barrel, the erosion wear was measured with a precision of ± 0.1 μm compared to ± 25 μm precision inherent in star-gauging measurements. The measurements were performed in-situ, without cleaning the bore surface, and in a relatively short time. The usefulness of this technique was demonstrated by the measurement of wear due to projectiles with plastic bands and $TiO_2$ wax coatings.

Preliminary results on the use of activated plugs to extend the technique to larger caliber guns are inconclusive but somewhat encouraging. It is possible that starting with a new tube of a large caliber, all of the problems encountered with the 20 mm barrel could be overcome. However, recent results with plugs in large barrels at BRL[6] and CALSPAN[7] indicate that there is a useful life of a plug which is short compared to wear life on a tube. Since it is felt that wear measurement by activated plugs will permit more efficient and possibly less expensive evaluation of gun tube erosion wear characteristics, additional tests are being instrumented. In addition, the use of inserts at the origin of rifling instead of plugs is being investigated.

The nozzle studies showing the general agreement between the mass loss measurement and the radioisotope measurement are a clear demonstration of the reliability of the methods. Also, the use of the activated nozzles in the evaluation of the relative erosivity of propellants has been demonstrated. In addition to the applications discussed, this technique can be used to measure wear from engine components, bearing surfaces, turbine blades and a variety of other surfaces. It is particularly useful in situations where the worn surface cannot be examined directly by more conventional methods or where surface cleaning may present problems. Some materials other than iron are also susceptible to this method but detailed calibration data needs to be compiled for these materials in order to allow very high precision measurements.


## ACKNOWLEDGEMENT

We wish to thank Messrs. T. Brosseau and R. Geene and Dr. J.R. Ward for their contributions to various stages of this experiment. Dr. G.M. Thomson contributed extensively to the design of the hardware required to interface the gun barrel to the beam tube of the accelerator. The activations of the various samples would not have been possible without the generous assistance of Messrs. D. Freil and C. Adams at the Tandem Laboratory of the University of Pennsylvania.


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6. T. Brosseau, and J.R. Ward, "Measurement of Heat Input into the 105 mm M68 Tank Cannon Firing Rounds Equipped with Wear-Reducing Additives," 1978 JANNAF Propulsion Meeting, Ineline Village, Nev., February 1978.
7. F. Vassalo, Private Communication.

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